Research Article

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A New Method for the Large-Scale Documentation of Pottery Sherds Through Simultaneous Multiple 3D Model Capture Using *Structure from Motion*: Phoenician Carinated-Shoulder Amphorae from Tell el-Burak (Lebanon) as a Case Study

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Abstract: This paper presents a new rapid, low-cost method for the large-scale documentation of pottery sherds through simultaneous multiple 3D model capture using *Structure from Motion* (*SfM*). The method has great potential to enhance and replace time-consuming and expensive conventional approaches for pottery documentation, i.e., 2D photographs and drawing on paper with subsequent digitization of the drawings. To showcase the method's effectiveness and applicability, a case study was developed in the context of an investigation of the Phoenician economy at the Lebanese site of Tell el-Burak, which is based on a large collection of amphora sherds. The same set of sherds were drawn by an experienced draftsperson and then documented through *SfM* using our new workflow to allow for a direct comparison. The results show that the new technique detailed here is accessible, more cost-effective, and allows for the documentation of ceramic data at a far-greater scale, while producing more consistent and reproducible results. We expect that these factors will enable excavators to greatly increase digital access to their material, which will significantly enhance its utility for subsequent research.

Keywords: 3D models, *Structure from Motion*, pottery, Phoenician amphorae, Tell el-Burak

1 Introduction

The development of digital methods for the documentation of archaeological artifacts has been given much attention over the last three decades (for an overview cf. Eslami, Di Angelo, Di Stefano, & Pane, 2020; Forte, 2010; Gilboa, Tal, Shimshoni, & Kolomenkin, 2013; Tanasi, 2020; Wilczek, 2017). More recently, *Structure from Motion* (*SfM*) 3D modeling has become widely used within the field of archaeology. Despite the great utility and take up of the technology for the documentation of sites and monuments more generally, using these methods is not yet a standard practice for artifact documentation. 3D modeling, if used at all, is usually restricted to small unrepresentative parts of larger assemblages.

Below, we present a new method for the rapid, large-scale 3D digitization of ceramic artifacts, which will allow researchers to undertake their recording more quickly, accurately, and cheaply and ultimately

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widen accessibility of new extensive data sets to interested researchers. This study focuses on ceramic data because of its ubiquity in many archaeological contexts, though a workflow similar to the one described here can easily be adapted to other classes of material culture (cf., e.g., Magnani, Douglass, Schroder, Reeves, & Braun, 2020). Despite the great research value of ceramics, scholars often limit their focus to a few basic themes: chronology, typological development, and the identification of regional associations of style/fabrics. Badreshany and Philip (2020), considering the research context of the Near East, point out that the difficulties and costs associated with the analysis and recording of pottery data mean it is often inadequately disseminated in publications and between groups of scholars, which has hindered the full realization of its explanatory potential. A plethora of research questions can be answered by studying pottery, including a range of complex cultural, social, and economic themes (for an overview, cf. Hunt, 2017). Our objective is to develop a method that increases access to ceramic data sets, encouraging further engagement and the development of new strands of research.

Cost and time-constraints on many projects allow for only a small portion of ceramic assemblages (where they are found in significant numbers) to be documented. Documentation is normally undertaken through 2D photography and initially through pencil drawings, which are time-consuming to produce. The quality also varies and is dependent on the skill and experience of a draftsperson. Such trained personnel are not always available to archaeological projects. Under these conditions, ceramicists must "curate" what they feel are the most representative items at any given time, despite the often changing nature of assemblages as sites are excavated and a greater understating of data sets is achieved. Confronted with these challenges, a more efficient and consistent method for the documentation of pottery has potential to significantly impact archeological research in areas and periods where ceramics are commonly found.

The digitization and 3D modeling of ceramics have been addressed in a number of publications (cf., e.g., Itkin, Wolf, & Dershowitz, 2019; Karasik & Smilansky, 2008; Wilczek, 2017; Wilczek et al., 2018; see there for further literature). 3D digitization of ceramics is often focused on producing prints for museum displays (e.g., Avella, Sacco, Spatafora, Pezzini, & Siragusa, 2015; Barreau et al., 2014) or other specific experiments like Opgenhaffen, Revello Lami, and Kisjes (2018) reconstruction of stamps from data gained through stamped sherds for further experimental research. Rather fewer studies have focused on large-scale documentation, and in cases where they have, a step-by-step-description is provided, but references concerning time needed for the individual steps are omitted (e.g., Wang, Qian, Liu, & Ji, 2019 focusing on typological questions) – a crucial consideration to encouraging uptake in our view. Our study shifts focus toward practical considerations: efficient collection of data in the field, under real world conditions (natural light, wind and dust), with limited access to power and limited time and resources while still providing reliable data at an increased scale.

We present below a new rapid, low-cost method for the large-scale documentation of pottery sherds using *SfM* to generate multiple 3D models simultaneously. To showcase the methods effectiveness and applicability, a case study was developed in the context of an investigation of the Phoenician economy at the Lebanese site of Tell el-Burak, which is based on a large collection of amphora sherds. The same set of sherds were drawn by an experienced draftsperson and then documented through *SfM* using our new methodology to allow for a direct comparison of time, cost, and accuracy. To the best of our knowledge, this is the first study that compares the conventional and digital documentation processes on a step-by-step basis considering the key practical factors highlighted above. Our objective is to provide an easy to deploy method that allows for the enhanced documentation of large ceramic data sets, which in turn will greatly increase their research potential by, for example, allowing for inclusion in big data projects focusing on ancient pottery, such as ARCHaide (http://www.archaide.eu/home) and the Levantine Ceramics Project (https://www.levantineceramics.org).

1.1 Introduction to the Site and Research Strategy

Tell el-Burak is a small three-period site (120 × 120, 20 m high) located on the Mediterranean coast of Lebanon 9 km south of Sidon. The tell (meaning hill in Arabic) is itself a construction of the Middle Bronze

Age I for the building of a large palace (Kamlah & Sader, 2019). After that time, the site was abandoned only to be reoccupied from the late Iron Age (Iron Age II, around 750 BC) until the end of the Persian Period (ca. 350 BC) (Kamlah, Sader, & Schmitt, 2016; Kamlah, Sader, & Schmitt, in press; Schmitt, 2019). A small farming community had settled on the tell during the late Mamluk and early Ottoman periods marking the final resettlement of the site (Shehadeh & Kallas, 2019).

The Iron Age remains provided the most substantial and diverse contexts as well as the largest assemblages of material culture, mainly consisting of fragments of ceramic vessels amounting to over 391,000 sherds (with over 32,000 diagnostics) – just from the 2013–2015 to 2017–2018 seasons. Considering that the site has been excavated since 2001 and has in every season produced vast numbers of pottery sherds, the scale of the assemblage and need for more efficient modes of documentation become apparent. Overall, the local Phoenician carinated-shoulder amphorae (CSA) constitute by far the most commonly found vessel group at the site (for more details cf. Schmitt, Badreshany, Tachatou, & Sader, 2018, pp. 7–9, 29) and, as such, are the focus of our study. CSAs serve as storage and transport containers for various agricultural products, such as wine and olive oil, so they represent important proxies for deeper insights into economic processes. More efficient systems for their recording and dissemination to the wider community of scholars are required to unlock their full interpretative potential. The multi-disciplinary study by Schmitt et al., 2018, greatly benefited from a large-scale recording of sherd data, which allowed for a nuanced understanding of morphological development and statistically robust calculations of their degree of standardization. A previous study based on a large set of CSA fragments from Tell el-Burak and using a multi-disciplinary approach lead us to the conclusion that the Phoenician homeland experienced economic growth during the late Iron Age and Persian Period (Schmitt et al., 2018). Furthermore, this economic growth seems to have been based on agricultural produce. In an independent study, based on the analysis of the plant remains found in the Iron Age contexts of Tell el-Burak, Orendi and Deckers (2018) had come to a similar conclusion. This interpretation, however, stands in conflict with the traditional conception of the Phoenician economy.

Conventionally, the Phoenicians are seen as a "nation of traders" who specialized in the manufacture of precious item, such as ivory carvings, metal bowls, and purple cloth, which they shipped all around the Mediterranean and beyond to gain profits (e.g., Markoe, 2003; Master, 2003; Sommer, 2010). The possibility of an extensive and substantial agricultural production in the Phoenician homeland has so far been denied in the scholarly literature (e.g., Aubet, 1997 [1993], p. 16, 55–57; Bondì, 1995, p. 276; Markoe, 2000, p. 94; Mater, 2003, p. 57). We are now challenging this long-held notion (Schmitt, forthcoming).

Building on our previous work, we have initiated a large-scale, multi-dimensional project which will provide and analyze the necessary data to put our hypotheses on firmer ground.[1] One component of this project is the study of a large set of CSA sherds from Tell el-Burak, Sarepta, and Beirut (in total 1,800 sherds). To manage the necessary documentation of this large corpus of samples, the conventional methods for pottery documentation seemed not to be adequate given the limited resources of the project.

1.2 Rationale

In May 2018, we conducted a 2-week pilot study based on site developing and testing the suitability and efficiency of multiple 3D model capture using *SfM*. The set-up and workflow were devised by Fanet Göttlich in cooperation with Helen Gries and Aaron Schmitt before the field campaign (for details see Section 2.2). The pilot study was based on 187 CSA sherds. Contemporaneously, the same sherds were documented by Andrea Kilian using conventional methods, i.e., drawing and taking 2D photographs (see Section 2.1). The time required for each step in both workflows was recorded to enable a comparison of efficiency.

1 Project title: "Beyond purple and ivory – An investigation of the Phoenician economy in their homeland based on agriculture and amphora production and distribution in southern Lebanon during the late Iron Age and Persian Period (ca. 750–350 BC)." This project is generously funded by the German Research Foundation since April 2021.

Our aim was to develop a low-tech and low-cost data acquisition method which could be used in the field and/or during study seasons. Considering real-world conditions, we focused on these important parameters:
(1) The method should be able to be deployed without constant access to electricity.
(2) The equipment should withstand extreme climatic and environmental conditions, such as heat and dust.
(3) Ideally one person should be able to carry out the work effectively and novices should be able to undertake the work unsupervised after a short introduction.
(4) The whole process of data acquisition, processing, and preparation of illustrations should significantly increase the scale of ceramic recording relative to conventional methods.
(5) The results should be roughly as accurate as conventional methods and ideally would produce more consistent and reproducible outputs.

1.3 Descriptions of the Materials

For the pilot study, a set of 187 Phoenician carinated-shoulder amphorae (CSAs) found in late Iron Age and Persian Period context of Tell el-Burak were chosen. CSAs have a characteristic shape and are easily recognizable by their sharp shoulder carination. The vessels are wheel-made and thus possess axial symmetry. The body is elongated with different articulations from convex to parallel to concave (Figure 1). In their lower part, the walls taper to a pointed base. Rims of the earlier CSA forms are short with minor articulations and become very short and simple later on (cf. Schmitt et al., 2018, pp. 8–9). Only CSA fragments with completely preserved rim and shoulder (until shoulder carination) were chosen for this pilot study as this part of the vessel underwent clearly recognizable and quantifiable changes within the late Iron Age and Persian Period.

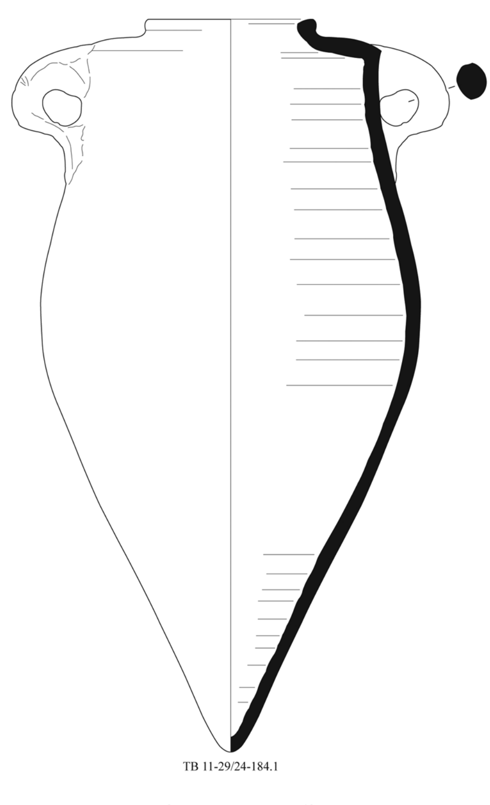


Figure 1: Persian Period amphora from Tell el-Burak (form type A-02C).

2 Description of Methods

In this section, we discuss traditional methods of drawing archaeological pottery and the advantages of the production of 3D models and 2D line-drawing generated through *SfM*. In our study, the time for each step of the respective process was repeatedly recorded. This allowed us to calculate the average time for each step. Through juxtaposition of these values, advantages and disadvantages of both methods will be highlighted.

2.1 Standard Practice in Conventional Pottery Documentation

The conventional visual documentation of pottery is based on a multi-step process involving pencil drawing, digitization, and taking photographs. The following section contains a short presentation of the standard pottery documentation system used by the Tell el-Burak archaeological mission. Drawings of selected sherds were mostly made after the field season by Rami Yassine who is professional draftsperson working from Beirut. For this pilot project, Andrea Kilian, an archaeologist with over 15 years' experience in drawing pottery for publication (cf. Kahl et al., 2012, pp. 196–201; Kahl et al., 2015, pp. 136–139; Kahl et al., 2017, pp. 141–145; Kilian, 2019), was responsible for the preparation of drawings and photographing.

The drawing of pottery across the discipline of Archaeology draws on many different techniques. Here, we have adopted the method described in Aston, 1998, pp. 13–26 because it provides a good step-by-step guide on how to achieve a pencil drawing with widely available equipment consisting of pencils with leads of 2–4 H hardness, a Vernier caliper, a profile gauge, tracing paper, liners, millimeter paper, and a diameter/radius chart (Figure 2; for additional introductions, cf. Orton & Hughes, 2013, p. 95; Shirvalkar, 2017;

Figure 2: Andrea Kilian at work drawing (surrounded by amphora sherds).

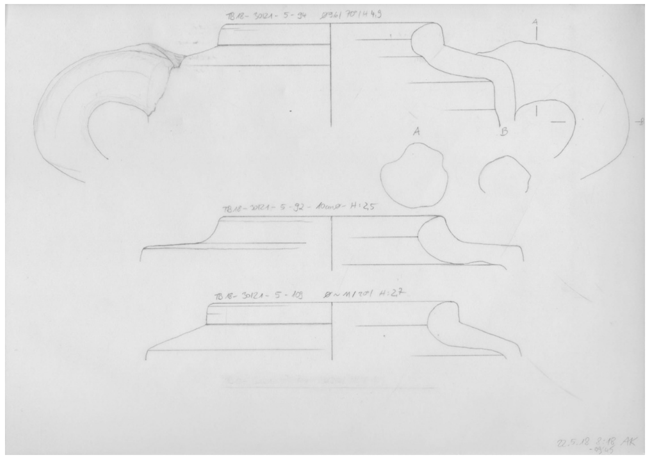


Figure 3: Scan of finished pencil drawings (original format of the paper sheet is DIN A4).

Rice, 2015, pp. 238–240). A scanner is also needed for digitizing all pencil drawings (Figure 3) for the subsequent digital “inking” via a vector-based program (see below and cf. Figure 4).

The time needed for drawing individual sherds varies and depends on the size of the fragment and its state of preservation. Based on drawing 187 sherds, the mean time needed to finish one pencil drawing was 14 min. When looking at this number, it has to be considered that the speed and quality associated with traditional drawing methods are heavily influenced by the experience of the draftsperson. While the method is easy to learn, it takes time to become skilled and efficient. An unexperienced person will, of course, need much more time to complete a drawing than a professional. In addition, inexperienced draftspersons are more likely to make mistakes and their drawings always need to be checked by a professional. Considering these factors and the experience of the draftsperson working on this project, the above figure should be considered as on the faster and higher-quality end of what is achievable.

The digitization of the finished pencil drawings takes place back in the office after the end of the excavation season. The scanned image is used for preparing a vector graphic with software like Inkscape or Adobe Illustrator to create an image suitable for printing (Figure 4).

On average, it took our expert 8 min to scan and vectorize one drawing and to rename the respective file. Those with less experience will of course require more time.

As part of our process, we take photographs of every sherd chosen for drawing. In publications, drawings and photographs are then illustrated together to maximize the information conveyed for each sherd (Figure 5). Though, it should be kept in mind that in traditional publications, the number of color photographs is often quite limited.

One photograph is taken of each side of the sherd, using a single-lens reflex camera (NIKON D7100 with 18–140 mm zoom lens) mounted on a tripod which is fixed to a table (with tape). Neither tripod nor camera need to be moved once this workstation is in place (Figure 6) allowing for the highest quality photos. We use a blue background to which a scale (10 or 20 cm depending on sherd size) and a color scale are attached. The blue background can easily be removed in a raster graphics editor like Adobe Photoshop when photographs are to appear in publications (see above and Figure 5).

The camera is connected to an iPad by Wi-Fi and can be remotely controlled through this device using the qDlsrDashboard App (V3.5.3).[2] The tablet screen shows the image area and a quality check of taken photographs can be done immediately.

2 For further information visit www.dslrdashboard.info; other solutions are available for remote control.

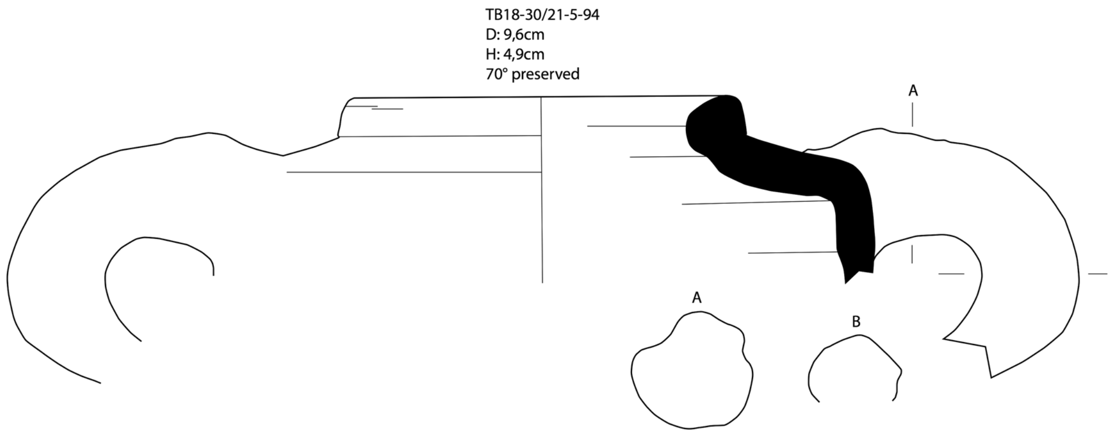


Figure 4: Digital drawing based on scanned pencil drawing (cf. Figure 3 for pencil drawing).

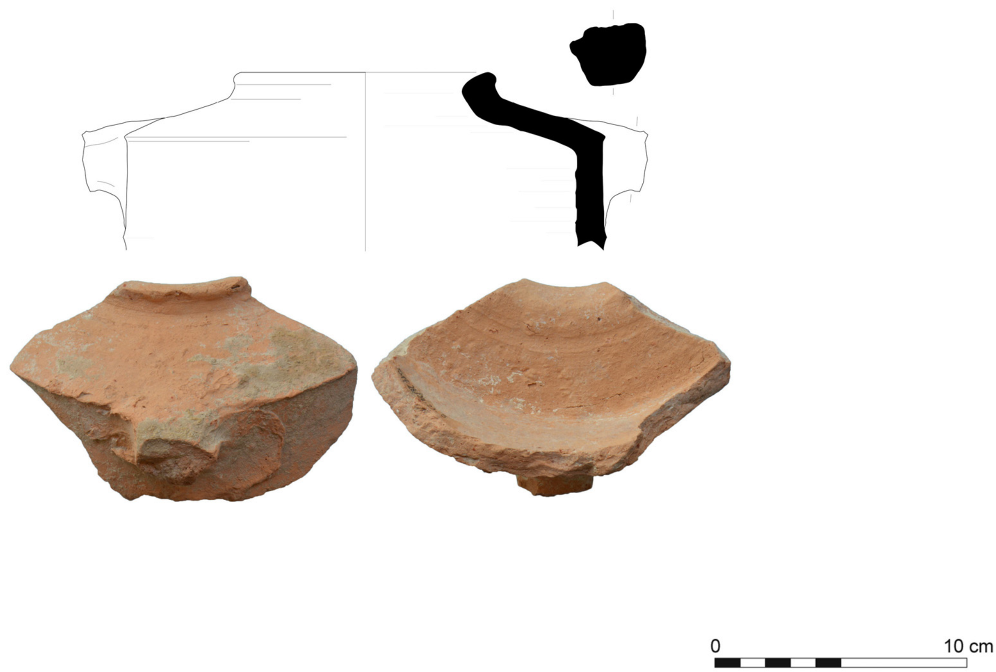


Figure 5: Digital drawing and photographs combined.

Images are later cropped to reduce file size, renamed according to our file naming conventions and inserted into a database. The mean time needed for photographing and further processing the images amounts to 5 min per sherd.

Drawing has long been established as the standard method for visual pottery documentation. A correct technical drawing conveys much more information to the (initiated) viewer than any other form of presentation (Orton & Hughes, 2013, pp. 95–100). However, certain features of the drawn fragments are more difficult or impossible to illustrate in a drawing unless a disproportionate amount of time is invested, e.g., color and overall shape of preservation. This additional information can often be provided by photographs (Orton & Hughes, 2013, pp. 100–103; Shirvalkar, 2017, pp. 223–229). 2D photographs also offer the (admittedly limited) possibility to compare the stylized drawing with the actual object. The great advantage of our method is that it results in a high-quality digital 3D model, numerous 2D photographs, and a more traditional line-drawing. These mediums should be seen as providing complementary information. The 3D

Figure 6: Workstation for taking photographs.

model represents an exciting new medium which gives a better sense of the original object and enables various types of measurements and analyses not possible with the traditional photos or line-drawings. Drawings and 2D photos allow for quick comparisons and are particularly useful in the preliminary stages of categorizing data.

The recorded and calculated times for the individual steps to produce illustrations using the workflow as detailed above are presented in Table 1. The documentation of one sherd in the field (drawing and photograph) takes 19 min on average. Another 8 min is needed for scanning and the digital retracing of the drawing.

Assuming a 4-week study season with 6 working days of 7 h (breaks not included), around 480 sherds could be drawn and photographed.

Table 1: Recorded time in minutes for steps in conventional documentation process

	1 sherd	100 sherds
Pencil drawing in the field	14	1,400
Photography in the field (including renaming and cropping of files)	5	500
Scanning and digital retracing in the lab	8	800
Total	**27**	**2,700**

2.2 3D Models

In this section, the process of generating 3D models using *SfM* is described. Using this method does not rely on expensive equipment or on a constant supply of electricity. The requirements as defined above led us to use *SfM* photogrammetry which guarantees the production of 3D models in sufficient resolution and accuracy (Luhmann, 2018; Pomaska, 2016). Other projects have successfully used low-cost structured light-based 3D scanners to capture 3D models (Wilczek et al., 2018, pp. 3–4) but these often need a stable power supply. The use of other scanning technologies was ruled out because of high acquisition costs, the necessity of uninterrupted power supply and the sensitivity of most electronic equipment to environmental

influences (cf., e.g., Karasik & Smilansky, 2008; Wilczek, 2017, p. 25 with further literature). Our essential equipment for using *SfM* photogrammetry consists of (cf. Figure 8):
– a digital single-lens reflex (DSLR) camera (in our case: Canon EOS 70D) with fixed focal lens (35 mm) and ring light mounted on the lens (Walimex pro Macro LED)
– a tripod
– a light tent
– a manual turntable (automatic turntables are available, but need power supply)
– a stand with eight attached clamps (the so-called “pottery tree;” cf. Figure 7).

A suitable camera and the equipment needed to recreate our rig can be readily acquired online for less than 900 Euros. The “pottery tree” was devised and assembled by Fanet Göttlich inspired by the previous work of Karasik and Smilansky (2008). The individual components are cheap and also easily available. Each clamp can hold one ceramic sherd. Eight clamps were fixed to the “pottery tree” allowing for the capture of eight sherds simultaneously. Depending of the size of the fragments, the addition of eight further clamps is possible offering further reduction in recording time per sherd over the figures presented below.

Regarding personnel requirements, one person can handle all steps described for data acquisition. However, one additional person preparing the next batch of sherds and removing photographed would speed up the process significantly.

All photographs were made in bright shade, avoiding direct sunlight. The light tent and ring light mounted on the lens of the camera ensured diffuse-light and the capture of neutral images. The camera was calibrated once a day with the calibration display and calculation of Agisoft Metashape (ASM) to reduce the impact of lens distortion. The “pottery tree” was placed on the manual turntable inside the light tent. The use of an automatic turntable would speed up the process, but depends on constant power supply (which could be provided by battery). Several markers for dimensional accuracy were placed on the turntable and around the “pottery tree.” The camera was mounted on the tripod and placed in front of the light tent at a distance of approximately 50–100 cm. This distance was optimal for our lens configuration but may vary for different lenses. The height of the camera depends on the height of the table and the different acquisition positions (Figure 8).

As one part of each ceramic sherd was covered by the clamp holding it, the recording had to be done in two passes with clamps fixed to a different part of the sherds for the second pass. The operator must ensure that the sherds are positioned and so their entire surface will eventually be photographed from multiple angles.

A black background provided better results with masking (see below) the images automatically and obtaining better geometric results at the edges.

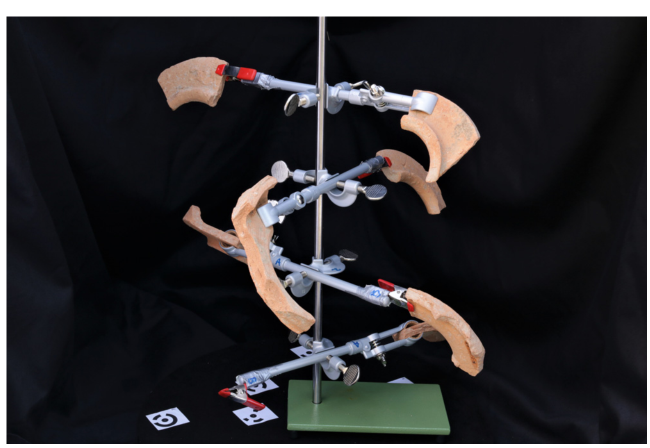


Figure 7: “Pottery tree” with sherds held by clamps.

Figure 8: Recording scenario with light tent and “pottery tree” (background color was later changed to black).

For each pass, 90–100 shots in four different camera positions and angles were taken, i.e., 23–25 shots per revolution of the turntable (Figure 9). The turntable was manually turned by approximately 15° before each shot. This angle guaranteed overlap of around 80% between adjacent images, which is necessary for a complete calculation of the object surface. The time needed for the two passes amounts to 25 min.

After careful consideration, we decided to use the ASM Professional software (version 1.4.2 and higher; former AgiSoft PhotoScan Professional) and MeshLab (version 2016.12) in combination for the calculation of the 3D models. MeshLab proved valuable for refining the outputs of ASM in intermediate stages. Texturing was done in ASM. As an alternative to ASM, RealityCapture is available (for a detailed comparison of the two programs, cf. Kingsland, 2019).

The processing was undertaken as follows. First of all, images of each of the two passes must be imported as separate Chunks (data blocks). An image of the background and the empty “pottery tree” must be taken as well to create a mask for all images using the ‘from background’ function in ASM. Using these masked images improves the point cloud while reducing the time needed for processing and formatting the models for alignment. With these masked images the “Aligning photos” command can be started, which calculates the camera positions and the sparse point cloud. Consequently, the dense point cloud will be calculated in high quality. Masking removes the background and mostly eliminates the need for editing of the point cloud. For referencing the data, the markers (fixed to the turntable) must be defined on the images as points and the corresponding distances need to be entered as scale bars. To achieve higher accuracy, the markers should be tagged several times in different images. Afterwards, the meshes can be calculated in high quality (Figure 10).

After the mesh is created, a separate Chunk must be created for each sherd by copying the main Chunk, deleting the other sherds and renaming the Chunk according to the sherd ID and the pass. Adhering to clear

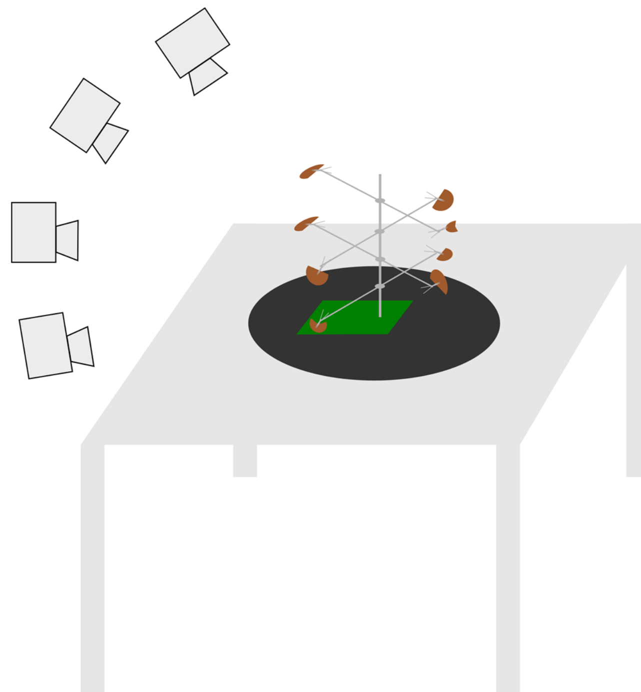


Figure 9: Camera positions.

file naming conventions is of importance for distinguishing the passes and the single sherds. After completing this step, two Chunks exist for every single sherd.

The Chunk for the first and second pass of each sherd must be aligned to each other. The automatic alignment function in ASM rarely completes this step satisfactorily. Therefore, a marker-based alignment must be used, where identical points are identified and labeled with additional reference points on both models. Subsequently, the two passes/Chunks are merged. The result of the merged model in ASM, however, is often unsatisfactory, so the Alignment of the two chunks is done again in MeshLab which in our experience provides more accurate results. The two meshes of the same sherd must be exported from ASM to continue editing in MeshLab where the alignment can be carried out much more precisely. The alignment in ASM is nevertheless necessary, because the texturing will take place again in ASM, and therefore we need the reference from the models to the images in ASM.

The last step of generating the 3D model of a single sherd is texturing. Before, images should be checked for blurred areas and overlays for the respective sherd. Blurry or otherwise unsatisfactory images must be disabled before the creation of the texture map. The result is the final textured 3D model (Figure 11), which is used for illustration and further analysis.

The time needed to generate one textured 3D model using the workflow described above amounts to 18 min per model on average.

The following steps for creating a 2D line drawing can be done in several programs like GigaMesh (Hubert et al., 2010), DACORD (Wilczek et al., 2018), or TroveSketch and Vessel Reconstructor (Kampel, Mara, & Sablatnig, 2005). As we had the software available, we decided to combine Vessel Reconstructor and TroveSketch, but similar workflows are also possible with the other two programs.

TroveSketch and Vessel Reconstructor were used for generating 2D views from multiple angles and as another advantage, can be used for vessel reconstructions (see Figure 12). In TroveSketch, the sherd is orientated according to a grid and rotation angles and orthogonal views from all six sides. In Vessel Reconstructor, a fuller reconstruction of the vessel from the original sherd is achieved by rotation about its axis. As part of this process, the profile of the vessel can be extracted which forms the basis for a 2D line drawing (Figure 12). The vessel's dimensions can be read in these two programs and provided in

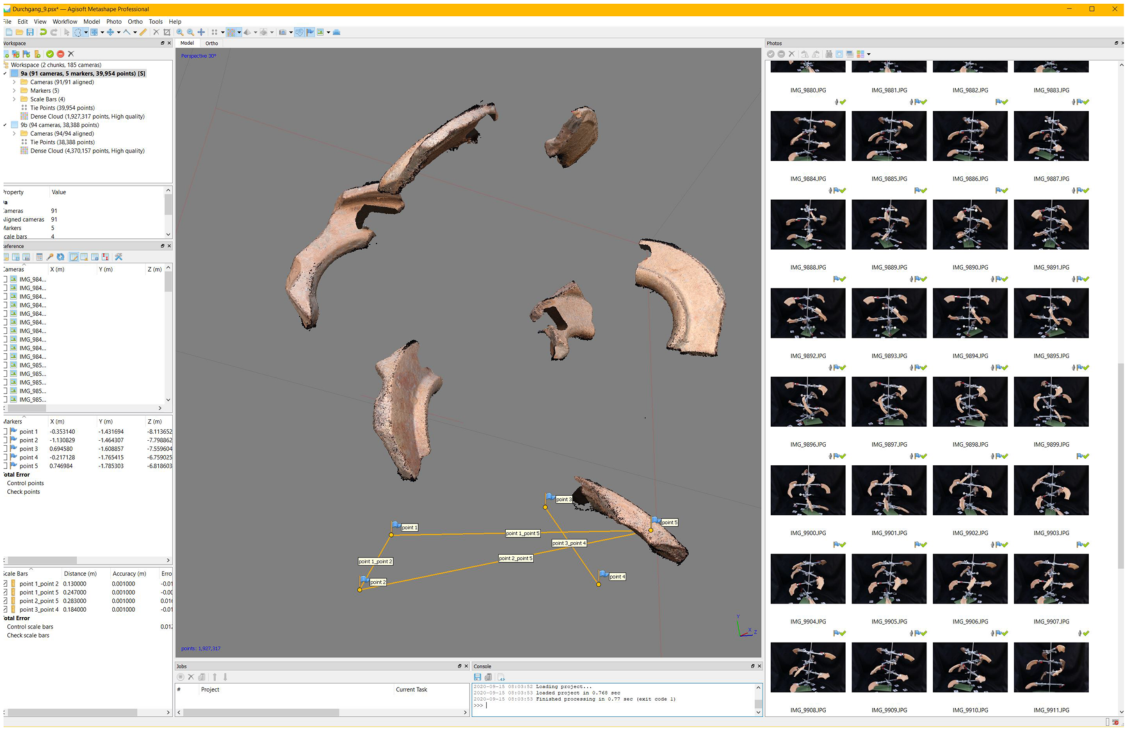


Figure 10: AgiSoft Metashape (ASM) interface.

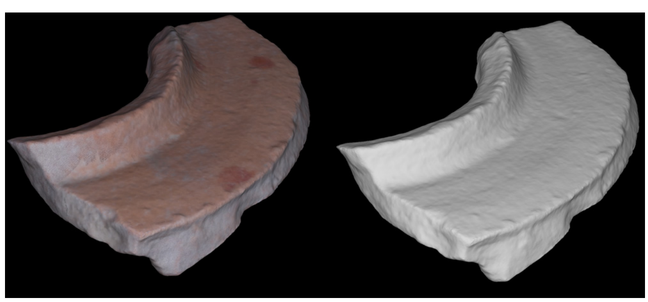


Figure 11: 3D model with texture color (left) and without texture information (right).

worksheets. GigaMesh and DACORD seem to be good alternatives for the costly TroveSketch and Vessel Reconstructor used in this study. Especially DACORD offers a wide range of different illustration possibilities and seems to have the potential for widespread use in archaeological research.

We have created a template in Word for a worksheet (Figure 12), in which all relevant information for each sherd from the various software programs can easily be compiled. This worksheet can be used for both print and electronic publication while the 3D model can be opened in a virtual viewer.[3]

The time needed to create illustrations according to the workflow detailed above amounts to 12 min per sherd on average.

Once the feasibility of the individual steps was optimized, the time for the processes could be measured. Recorded times include the complete process from setting up the tripod to file naming. The setup of the workstation was not considered, but it only takes a few minutes per working day. The calculation period for

3 The 3D models should be published in an online repository with 3D viewer (e.g. SketchFab, https://sketchfab.com/) to share it with the international research community.

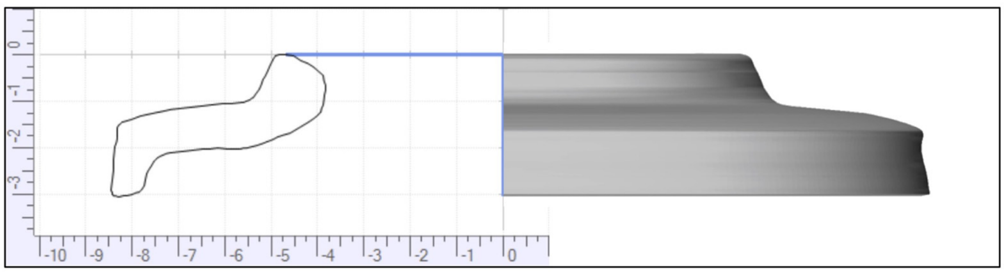
Datasheet amphorae

General info

Sherd ID:		Site:	
Scale:			

Measurements (in mm, inclination in degrees)

Dm. opening:		Neck length:	
Shoulder length:		Shoulder thickness:	
Shoulder inclination:		Dm. at shoulder carination:	



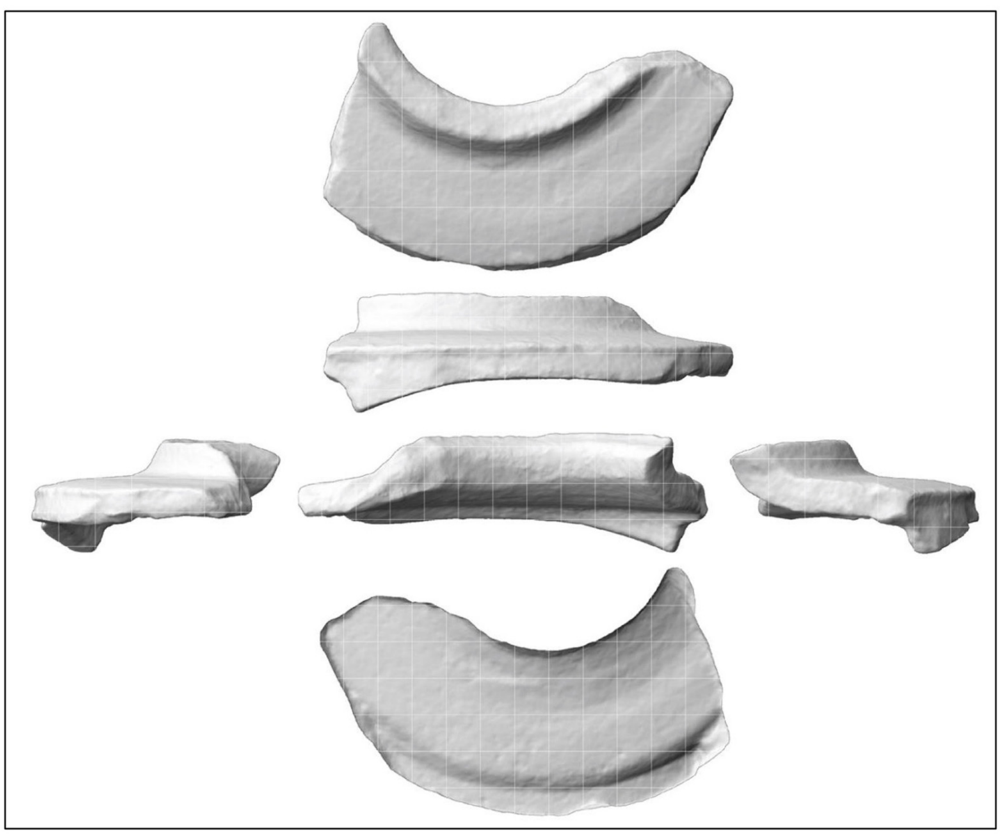


Figure 12: Worksheet.

the generation of the point clouds from the images was not considered. The times depend very much on the available hardware and vary between 2 and 16 h. Furthermore, only a few manual operations are necessary to perform the calculation because batch processing is possible.

3 Results

The values for the subsequent manual processing of the point clouds are summarized in Table 2. In Table 2 we also show the impact of increasing the simultaneous recording from 8 to 16 pieces, which significantly reduces the recording time on site (A). As the number of images remains almost the same with 16 sherds captured simultaneously, the time needed to generate point clouds does not change significantly. The processing time (P) includes the rectification of the whole point cloud in ASM. The generation of a single 3D model (G) includes the merging in MeshLab and the texturing process in ASM for finishing the 3D model. The results of screenshots and vessel reconstructions needed for the worksheet (Figure 12) are given in step (R). All the recording values and metadata of each single object are kept in a database and the model itself is stored as an ASCII – PLY file as recommended by Ianus and the London Charter (London Charter, 2009; Trognitz, 2017).

The recorded and calculated times for the individual steps to generate 3D models and produce illustrations using the workflow as detailed above are presented in Table 2. Based on the 8-sherd workflow, the creation of one 3D model requires 25.5 min. This is further reduced using the proposed 16-sherd workflow. The production of illustrations for the worksheet needs another 12 min.

It is worth emphasizing at this point that only the photographic acquisition of data (A) has to be done in the field. All later steps can be conducted at the home research facilities. This means that only 2.75 min are needed for data acquisition for each sherd making it possible to document thousands of sherds during a typical excavation or study campaign with relatively small investment in staff (one to two people per workstation) and equipment.

Assuming a 4-week study season with six working days at 7 h (excluding breaks) approximately 3,600 sherds can be photographed. Additional workstations could increase this number proportionately.

Table 2: Duration of individual processing steps in minutes

	8 sherds			16 sherds		
	Each tree	**Each sherd**	**100 sherds**	**Each tree**	**Each sherd**	**100 sherds**
Acquisition (A)	22		275	25		156
Processing (P)	38		475	50		313
Generate 3D model (G)		18	1,800		18	1,800
Intermediate total		**25.5**	**2,550**		**22.7**	**2,269**
Produce results (R)		12	1,200		12	1,200
Total		**37.5**	**6,300**		**34.7**	**5,738**

4 Discussion

The results of this pilot project prove its utility. The prerequisites as defined in Section 1.2 for the successful application of a new digital method for pottery documentation have been fully met. We have shown clearly that the acquisition of 3D models using *SfM* has major advantages over the conventional method of visual pottery documentation by drawing and photographing.

The equipment needed to use the digital method should be affordable and obtainable by most archaeological projects and does not depend on a stable electricity supply. Furthermore, the proposed rig can be set up in almost every environment and used under different climatic conditions. The equipment is also lightweight and easy to transport and conventional which is an important consideration. The import of 3D scanners and other unusual technical equipment into some countries can be difficult. Our rig is made of commonly available low-cost equipment which should be permitted by the customs regulations of most countries.

The digital method can be applied by novices after limited training and does not require an aptitude for drawing.

In total, the conventional method is 10 min faster per sherd than our proposed method. However, using our method the time needed for documentation in the field is considerably shorter, meaning seven times more pottery can be recorded in a 4-week season as described above (3,600 digital vs 480 manual recorded sherds). This is a major advantage of the digital method as it frees up a lot of precious resources which can then be used to engage in other essential processes around site or of artifact documentation more generally, such as the description of form and fabric and sampling.

Although conventional drawing is technically faster, our method produces a rich array of digital media, which is easily sharable and enables a far-greater depth of analysis and engagement than possible with 2D drawings and photographs alone. Of course, the quality of the results and the time required to generate 2D drawings are highly dependent on the skill of the individual draftsperson and the conventions used (Gilboa et al., 2013, p. 1330). In the absence of international standards, drawing style can, therefore, vary considerably in appearance and detail (cf. Orton & Hughes, 2013, p. 99, Figure 7.3). In contrast to this, the drawings produced based on 3D models have potential for greater consistency and reproducibility.

Of course, with our method additional resources are needed away from the field to process the generated data, but it is less time-dependent and in general, less costly to process data away from the field. It should also be noted that the sample set chosen for this pilot project consisted exclusively of CSA sherds which are relatively easy to draw because they do not exhibit special features, such as decoration. It is to be expected that more complex sherds will increase the time needed to finish one drawing.

We would like to emphasize that even with the employment of the method presented here, the services of draftspersons will still be needed to draw more complicated shapes and decorated pottery. Our method aims at incorporating exciting new digital technologies to increase the scale of what was traditionally possible. In addition, we hope our method facilitates documentation and contributes to a reduction in workload for antiquities authorities in developing countries, which often face immense challenges and are under-resourced. In the context of our work in Lebanon, we hope to further develop this method in cooperation with our colleagues in the local antiquities department, who are experienced in ASM, to decrease the effort needed to document ceramics and other artifacts under their care.

5 Conclusion

In this paper, we have juxtaposed the conventional method of visual pottery documentation with a newly developed method based on *SfM*. This study clearly demonstrates the utility of this new digital technique and offers clear advantages for pottery documentation in the field, allowing researchers to increase their documentation output sevenfold in the field. The main product of our method, highly accurate 3D models with photorealistic textures, is currently the best possible proxies for the actual sherd material. We hope an increase in their productions and accessibility will encourage the development of a range of new analytical techniques. Once made accessible on the internet, 3D models offer a highly accurate digital facsimile that facilitates access to large-scale ceramic data sets for a wider community or researchers, thereby reinvigorating interest in ceramics and helping to situate them within broader research frameworks (Badreshany & Philip, 2020). In this work we have focused on the research potential of increasing the scale of digital 3D models of ceramics, however, their utility as educational tools in teaching and public engagement settings cannot be overstated.

In the future, we will strive to further optimize the workflows in terms of recording quality and processing time. A handbook for using the method will be developed to ensure correct application of the method and problem solving. A key goal for the future is to develop an automatic or semi-automatic workflow which would produce a fully compiled worksheet.

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